SYNOPSIS

ON

Study of Quantum Entanglement Properties of Light in Nonlinear Optical Phenomena

SUBMITTED

BY

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SYNOPSIS

Topic of the Ph.D.:

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1. Introduction:

A light-matter interaction in certain aspects result has been in agreement with experiments without quantization of the optical field. Such a semi-classical description is not sufficient to describe, photo-count distribution, 'non-classical' states of light such as optical correlation, anti-bunching of light, sub-Poisson photon statistics, degree of coherence of light, squeezing of light, entanglement of quantum states, etc. These can only be explained by quantum theory of light in which both light and matter are treated quantum mechanically.

As mentioned above non-classical states of light such as squeezing of light, anti-bunching of light and entangled states are of interest owing to its low-noise property and potential applications in quantum information. It is the fundamental property of any optical system, in which the quantum fluctuations is not randomly distributed in the field quadrature components. It present in all kinds of electromagnetic field states, including vacuum state [1].

Moreover, photon antibunching [2] is nothing but the measures of photon anti-correlation. The phenomenon by which photon prefers to come separately instead of cluster. This phenomenon confirms the corpuscular nature of radiation. The quantum entanglement is one of the most characteristic properties that makes quantum theory distinct from classical theory. Since entangle states have been put forward by Einstein et al. [3] to verify completeness of quantum mechanics, they have been attracting extensive attention in physical field. Recently, following the development of quantum information, the entangle states are considered as a kind of important physical resource. It plays an important role in quantum information science due to its nonclassicality properties. It is considered as the fundamental resource of quantum information processing such as quantum teleportation [4-9], quantum computation [10], quantum cryptography [11], quantum cloning [12] and etc.

2. Preliminary review of literature/state-of-the-art:

Over the past decades, a lot of notable work has appeared in the literature on the generation of higher-order squeezed laser light as resource for quantum teleportation and their theoretical prediction and experimental confirmation by various nonlinear phenomena [13-22]. In this quantum teleportation, first proposed by Bennett *et al*. [4] for systems of discrete variables and later on proposed by others [5-9] for continuous variables (CV) using Einstein-Podolsky-Rosen (EPR) entangled state [3] and become indispensable for theoretical and experimental quantum communication and information processing [8,9,23,24]. It is a technique that can transmit an unknown quantum state from a sender to a receiver at a distant location via a quantum channel with the help of some classical information. Furthermore, distributed entangled states make it possible to send an unknown state for a long distance. It does not transport energy or matter, nor does it allow communication of information at the super luminal (faster than light) speed. It is well known that the success of the communication of information can be characterized by the teleportation fidelity. When the output state is exactly the same as the input state, the fidelity is equal to unity. Earlier, Horodecki *et al.* [25] proved the relation between the fidelity of teleportation and the quantum

channel. The quantum teleportation network has also studied by Loock *et al.* [26] using multipartite entanglement for CV. Takei *et al.* [27] also established an operational method for evaluation for quantum teleportation of a squeezed state using fidelity and discuss its classical limit. Anno *et al*. [28] has investigated continuous variable quantum teleportation using non-Gaussian states of the radiation field as entangled resources and showed that optimized squeezed Bell-like resources yield a remarkable improvement in the fidelity of teleportation both for coherent and non-classical input states. Recently Zhang *et al*. [29] discussed the dependence of fidelity in teleportation on the squeezing parameter of single-mode squeezed coherent states. Truong *et al.* [30] and Wang *et al.* [31] have recently given the concept of higher-order properties of non-classical light and entanglement in the two-mode in lucid manner. The nonlinear response of the system to the radiation field in nonlinear optical phenomenon is expected to plays a great role. These studies can be expected to lead to new fundamental insights of an optical field of interest to the research community in the arena of quantum optics, nonlinear optics, atomic physics, molecular physics and biological physics.

3. Problems to be investigated:

Quantum low-noise is the fundamental property of any optical system. It present in all kinds of electromagnetic field states, including the vacuum state. Light with unusual quantum noise properties is called nonclassical light and occurs e.g. in the form of squeezed light, photon antibunching, sub-Poisson photon statistics. Out of which squeezed laser light as a resource has generated for reducing the optical noise of an optical signal below the vacuum limit. It has been attracting attention in quantum optics over the last decade. Up to now most theoretical and experimental investigations have been carried out exclusively in the time domain [13-22]. These phenomena have lot of potential applications but are still to be investigated for designing teleporting systems with nonclassical states to improve the quality of the teleported quantum state using entangled state. Hence in view of these problems our key interest to study entangled squeezed light in various multi-photon nonlinear optical phenomena.

4. Objectives of the research:

The main objective of the research will be to study **quantum entanglement properties of light in nonlinear optical phenomena.**

In the selection of nonlinear optical phenomena like higher-order harmonic generation, multi-photon absorption processes will be given more importance as not much of work has been done to investigate the entangled squeezed state as resource for quantum teleportation in these processes. In addition to the higher-order squeezing study of another type of higher-order squeezing like the sum of the frequency generation and difference of the frequency as well as squeezing on photon numbers will also be included as resource for quantum teleportation.

5. Research questions and or Hypotheses:

A state is called nonclassical if its Glauber Sudarshan P function is negative or more singular than a delta function [1]. In these situations, quasi probability distribution P is not accepted as classical probability and thus we cannot obtain an analogous classical state. Quantum nature of anti-bunching of photons reflects the generation mechanism of photons. This is exactly characterized as the probability of detection of one-photon pulse is greater than that of a two-photon in a bunch and that is greater than the probability of detection of a three-photon in a bunch and so on. As such squeezed state and photon antibunched state are well known nonclassical states.

Quantum entanglement of two squeezed states is a property of a set of subatomic particles whereby a quantum characteristic (such as spin or momentum) of one particle is directly and immediately correlated with the equivalent characteristic of the others regardless of separation in space. There are many criteria as the measures of entanglement have been proposed for continuous variable systems [32-36]. In experiment, the first observation of quantum teleportation has been accomplished with two-mode squeezed states [6, 8]. Therefore, generation and manipulation of nonclassical states of continuous variable systems are the important elements in the quantum information processing.

6. Research design & Research methodology:

Our investigation will be based on quantum mechanical technique of setting up of Hamiltonian for various multi-wave mixing processes and establishing Heisenberg equations of motion of the quadrature operators involving the real and imaginary parts under the short-time scale for various field operators. These equations are exactly unsolvable in closed analytic form under weak pump. The short-time approximation approach is simple and enables us to derive explicitly short-time quantum statistics within the interaction time in a systematic way. It is possible to obtain much simpler approximate analytical formulas describing the variances, when the photons number is very large ($|\alpha|^2 \gg 1$) and short-time scale $gt << 1$ ($gt \sim 10^{-6}$). Such solutions provide information for more detailed computations and make it possible to determine, in a straightforward way, all the possible states of light of the field exhibiting anti-correlation, anti-bunching, correlation bunching and full coherence. As the pump field, nanosecond or picoseconds pulse laser may be used. The computations will be done using MATHEMATICA. Entanglement properties of the radiation field will be investigated according to entanglement criterion [33, 35].

7. Tools to be used in the collection of data and analysis: N/A

8. Significance of proposed work:

Squeezed light with low-noise has many attractive potential applications in e.g. optical telecommunication [37], precision measurements such as gravitational wave detection or noise-free amplification of signals [38,39], optical computing [40], the solution to cosmological problems [41], detection of biological tissues [42] and so on. Higher-order antibunched light is essentially a multi-wave version of anti-bunching which is more useful as a single-photon source [43] for quantum cryptography [44].

In recent years, entanglement in continuous-variable systems that can offer an advantage in quantum information processing has been attracted great interest both theoretically and experimentally work [45-47]. Therefore, generation and manipulation of nonclassical states of continuous-variable systems are the important elements in the quantum information processing. These studies can be expected to lead to new fundamental insights of an optical field of interest to the research community in the arena of quantum optics, nonlinear optics, atomic physics, molecular physics and biological physics.

These studies can lead to designing good quality of teleporting systems and maybe expected for the fabrication of future teleporting devices.

9. Research limitations and future work:

The limitation of short-time approximation including real and imaginary parts of the coupling constant can be removed by using some mathematical technique. The phase dependence of the quadrature component may be included in the study. The research outcome would be utilized

to work further in the field of quantum information and quantum computation. The scope of future work is manifold.

At present strong possibilities of future work appears in the following:

- Experimental verification of the theoretical results of the present work.
- Use of squeezed light as resource in quantum teleportation.
- Entanglement properties of the radiation field can be used for quantum information.

These results offer the possibility of designing future teleporting devices and may be improving the performance of many optical devices and optical networks.

10. Tentative chapterizations:

Chapter 1: Introduction

Chapter 2: Entangled squeezed laser as resource for quantum teleportation

Chapter 3: Antibunching and entangled states of light

Chapter 4: Higher-order squeezing and entangled states of light

Chapter 5: Summary and Conclusions

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